

Purdue University Purdue e-Pubs

Department of Electrical and Computer
Engineering Faculty Publications

Department of Electrical and Computer
Engineering

January 2009

A case study of system power efficiency loss mechanisms in a multijunction, spectral splitting, concentrator solar cell system

J. R. Wilcox

A. W. Haas

J. L. Gray

R. J. Schwartz

Follow this and additional works at: <http://docs.lib.purdue.edu/ecepubs>

Wilcox, J. R.; Haas, A. W.; Gray, J. L.; and Schwartz, R. J., "A case study of system power efficiency loss mechanisms in a multijunction, spectral splitting, concentrator solar cell system" (2009). *Department of Electrical and Computer Engineering Faculty Publications*. Paper 15.
<http://dx.doi.org/http://dx.doi.org/10.1109/PVSC.2009.5411606>

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

A CASE STUDY OF SYSTEM POWER EFFICIENCY LOSS MECHANISMS IN A MULTIJUNCTION, SPECTRAL SPLITTING, CONCENTRATOR SOLAR CELL SYSTEM

J. R. Wilcox, A. W. Haas, J. L. Gray, and R. J. Schwartz
Birck Nanotechnology center, School of Electrical and Computer Engineering,
Purdue University, West Lafayette, IN 47907

ABSTRACT

In multijunction solar cell concentrator systems, it is important for system and cell designers to understand the relative magnitude of each loss mechanism. This investigation of potential system power efficiency improvements for a high-efficiency concentrator system focuses on quantifying the effects that various known loss mechanisms have on the overall system performance. Each of the loss mechanisms that were investigated play a part in the degradation of the device's performance and each of these losses can be reduced by appropriate engineering. This paper will address the extensive optimization of the system power efficiency of a multijunction concentrator solar cell system for the DARPA Very High Efficiency Solar Cell (VHESC) project. These results are useful to the system and cell designers and guide the efforts to reduce losses and to maximize the system power efficiency.

INTRODUCTION

When trying to improve state-of-the-art cells in multijunction concentrator systems, it is important for system and cell designers to understand the relative magnitude of each remaining loss mechanism so as to

identify which are the most important. The purpose of this study is to identify areas for potential improvement that require only creative engineering solutions and not major breakthroughs in material quality or device design. We will show that these losses provide enough potential gain to significantly improve system performance. This will help the system designers to know which losses are important and which are not. Care was taken to ensure that losses were not counted twice; this in turn allows us to view the total potential gain as the sum of the individual component improvements. In the following sections, we will discuss these losses in detail and calculate the magnitude of each for a modeled four junction concentrator system composed of a GaInP/GaAs mid-energy stack and a GaInAsP/GaInAs low-energy stack (see Figure 1) [1,2,3,4].

The system consists of optical lens and a dichroic mirror that spectrally splits and focuses the incident light. The high energy photons are reflected off the dichroic mirror into the mid-energy stack, while the lower energy photons pass-through the dichroic onto the low-energy stack. The top cell in each stack is made of a wider band gap material. This allows it to collect the higher energy photons, while the lower energy photons pass through the top cell without being absorbed, and are collected by the bottom cell.

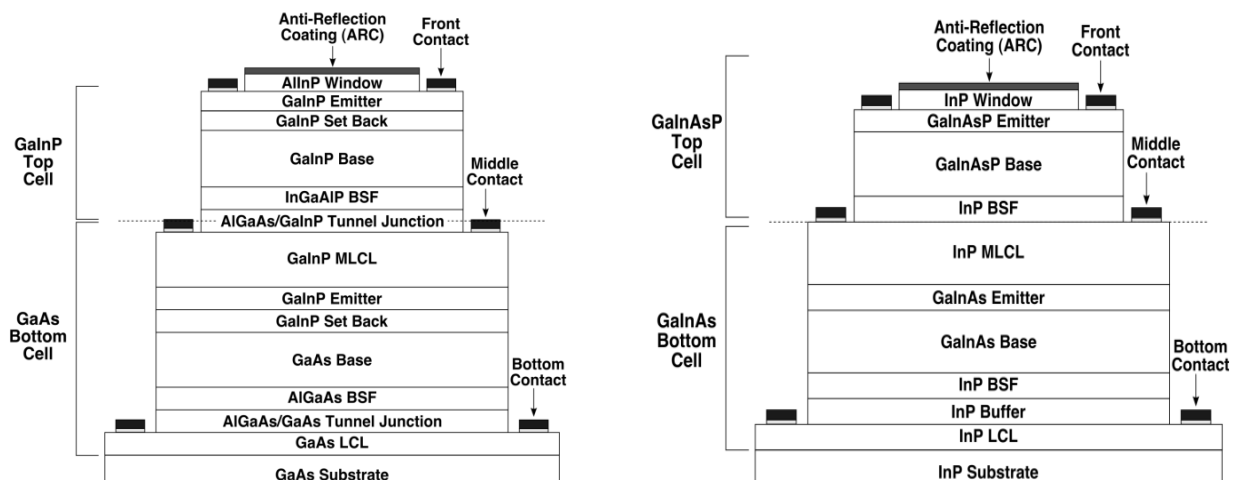


Figure 1. Mid-energy (left) and low-energy (right) cell stacks, used in the 4 junction solar concentrator [3,4]

MODELED SYSTEM POWER EFFICIENCY

Recent measurements of a four junction system show system conversion efficiencies near 39% [5]. The models show that the system's cells and optics can be improved via engineering solutions. Cell models can provide insight into areas in which system components can be improved and can provide an upper limit on the available efficiency improvement for each loss mechanism. This, in turn, allows device designers to appropriately prioritize their focus to more rapidly increase system performance.

Several types of models have been developed to determine these potential areas of improvement, ranging from diode models [6] to advanced numerical models using ADEPT [7]. In every case, model parameters are extracted from measured device performance in the neighborhood of the device operating points. Thus, even the simple models are reliable in evaluating areas and magnitudes of possible improvement for the operating conditions found in the system. Each of these losses will be explained in more detail.

The theoretical maximum system power efficiency (SPE) for a 4 junction solar cell system is ~61% [1]. After including 94% efficient optics, the maximum system efficiency is 57.3%.

SYSTEM POWER EFFICIENCY IMPROVEMENT CALCULATIONS

There are many effects that shape the overall efficiency of this system. The losses that reduced the efficiency of the cells include; internal and external resistance, fill factor (FF) degradation, absorption in the window layer and tunnel junction, non-illuminated cell area, grid electrode shadowing, dichroic mirror transition width, and losses associated with anti-reflection coating (see Table 1).

The losses are reported in absolute percentage points. The first line of this table shows the modeled 4 junction SPE for this concentrator system [8]. Some of the losses are very small, such as the absorption in the mid-energy tunnel junction. Other losses are much more significant, such as the window layer in the GaInP cell.

While in many cases it is unrealistic to completely eliminate these losses, it is possible to partially decrease all of them. Knowing the relative magnitude of each of these losses helps system designers understand the affect each loss has on the overall system efficiency. Information like this has already been helpful in directing the cell designers to reduce the absorption in the mid-energy tunnel junction.

RESISTIVE LOSSES

Sheet/grid/frame resistance

Lateral conducting layers can be a significant source of power loss. The importance of this power loss is determined by the magnitude of the conducting layer's sheet resistance, the geometry/layout of the cell, and the distribution of the illumination across the cell. The sheet resistance of the conducting layer can vary greatly depending on the material, the dopant concentration, and layer thickness as

$$R_{sheet} \approx (q\mu Nt)^{-1} \quad (1)$$

Where t is the conducting layer thickness, N is the dopant concentration, μ is the majority carrier mobility and q is the elementary charge.

These sheet resistance values, in addition to known cell geometry/layout, measured I_{sc} - V_{oc} values, and an ideality factor (determined from measured I_{sc} - V_{oc} values) allow the cell performance to be calculated. This calculation employs iterative methods based on an ideal diode model,

Table 1. System power efficiency and loss mechanisms*

	GaInP	GaAs	GaAsInP	GaInAs	Total
Modeled system power efficiency	17.7 %	9.5 %	9.4 %	2.3 %	38.8 %
Loss mechanism	GaInP	GaAs	GaAsInP	GaInAs	Total
Fill factor degradation	1.3%	0.27%	0.91%	0.26%	2.72%
Reflectance and angular dispersion	0.60%	0.81%	0.18%	0.016%	1.6%
AlInP window layer in mid-energy GaInP device	1.0%	0%	0%	0%	1.0%
Grid line shadowing/dark diode	0.40%	0.20%	0.061%	0.054%	0.72%
Dichroic Optimization	0.69%				0.69%
Border reduction	0.074%	0.16%	0.096%	0.072%	0.40%
Sheet/grid/frame resistance	0.14%	0.003%	0.09%	0.005%	0.24%
Absorption in mid-energy tunnel junction	0%	~0.12%	0%	0%	~0.12%
Totals	3.5%	1.5%	1.3%	0.41%	7.4%

* The losses are reported as absolute percentage point improvements.

which includes a grid of resistors that simulate the lateral conducting layer sheet resistance [9]. Additionally, this model includes the electrode resistance and dark-diode effects due to the shadowing caused by the frame and grid line electrodes. By comparing this simulated cell performance to that of an ideal diode model with the same cell parameters (I_{sc} , I_0 , and ideality factor), one may calculate the power that is lost due to the lateral conducting layer sheet resistance, frame dark-diode effects, and electrode resistance.

In the case of the multijunction, spectral splitting, concentrator system analyzed here, the low-energy and mid-energy stacks employ three lateral conducting layers each, as they are three-terminal designs. In both the mid-energy and low-energy cases, the emitter (the topmost lateral conducting layers) is much thinner than the middle and bottom lateral conducting layers. Thus, the sheet resistance of low-energy and mid-energy stack emitters (541.9 ohms/sq. and 150 ohms/sq., respectively) is much higher than that of the middle and lower lateral conducting layers (~10 ohms/sq. or less). Consequentially, the losses due to the lower two lateral conducting layers are negligible for both the mid-energy and low-energy cell stacks. The loss in the conductor layers was modeled directly using a distributed resistance model. First, the resistive losses were calculated using the measured resistance values. These values were then compared to the modeled cell performance assuming that the resistance had been eliminated.

Our calculations show the reduction in the SPE in the low-energy stack to be 0.095 absolute percentage points (with 0.09 absolute percentage points resulting from the emitter) and that of the mid-energy stack to be 0.15 absolute percentage points (with 0.14 absolute percentage points resulting from the emitter), for a total of 0.24 absolute percentage points (see Table 1). The total loss is quite low, which is the result of both stacks implementing two grid line electrodes in the active area of the device. This reduces the distance that carriers must travel to the electrodes, largely eliminating loss in the emitter. One should note that this calculation is based on a uniformly illuminated cell. For the non-uniform case, which is commonly the case, light is concentrated near the center of the cell, and the resistive losses would likely be increased slightly; however, grid line shadowing losses could increase greatly if the high intensity region falls on a grid line.

Fill factor degradation

In addition to power losses associated with lateral conducting layer sheet resistance, power loss occurs as a result of several other intrinsic and extrinsic factors. These factors can include losses such as those related to poor tunnel diode operation, faulty electrical contacts additional resistance and/or abrupt transitions in the electron affinity near the back of the cells. While additional electrical losses are easily detected by comparing

measured and modeled current-voltage curves, the specific sources of these losses are very difficult to identify. These losses will be grouped into one term labeled Fill Factor Degradation. Unlike lateral resistance, these loss mechanisms have not been measured directly. However, while the source of these losses has not been specifically identified, they are real and represent areas of potential improvement. They are inferred from the measured value of the FF [6].

Often these losses are added to the ideal diode model in the form of a series resistance, so that the current-voltage characteristics of the model match those that have been measured.

$$I = I_{sc} - I_0 \left(\exp\left(\frac{q}{nkT}(V - IR_s)\right) - 1 \right) \quad (2)$$

Where n is the device ideality factor, kT/q is the thermal voltage (0.0259 V at 300 K) and I_{sc} is the short circuit current.

We included this series resistance loss term in the numerical lateral resistance model. Figure 2 shows, for the mid-energy GaInP cell, the progression from the ideal diode model to a model which includes lateral resistance. Then series resistance is added to matches the measured current-voltage data more closely.

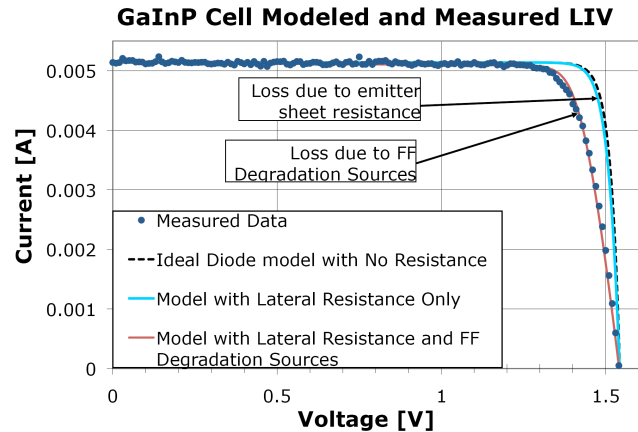


Figure 2. Modeled and Measured illuminated I-V Curves for GaInP Cell ~40X

Calculations show that 2.72 absolute percentage points are lost due to the FF degradation, making it the single largest SPE loss mechanism.

DEVICE GEOMETRY

Grid line shadowing/dark diode

As mentioned earlier, losses due to emitter sheet resistance can be kept relatively small by including grid line electrodes within the active area of the devices to shorten the lateral distance that carriers must travel.

While loss resulting from emitter sheet resistance only totaled 0.24 absolute percentage points, the potential gain associated with reducing this resistance is actually much greater. For the case in which the emitter sheet resistance has been reduced to a negligible level, the grid line electrodes can be removed. This eliminates the shadowing due to the grid lines. A distributed resistance model was used to model the cells with and the without grid lines. Calculations performed for uniformly illuminated cells show that this gain would be approximately 0.72 absolute percentage points, though this gain would likely be much larger for a non-uniformly illuminated cell. In this case the light is concentrated near the center of the cell where the grid lines are typically located.

Shading of the active area of the cells occurs as a result of the metallic grid lines placed in the active area of the cell. In the current cell designs, these are 10 μm wide. This results in one percent of the illumination being lost for each grid line. These losses also can be reduced with a higher aspect ratio for the grid lines or eliminated by adding pyramidal reflectors on the top of the grid lines (see Figure 3).

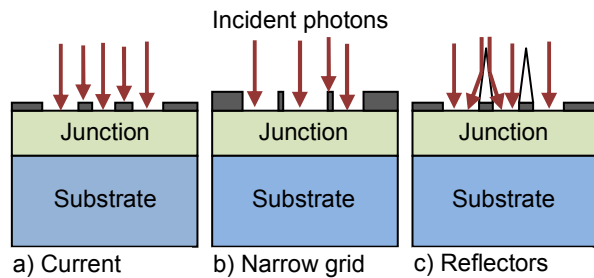


Figure 3. Diagram a shows the current design. Diagram b shows higher aspect ratio grid lines that could be used to reduce shadowing. Diagram c shows reflecting triangles over the grid lines.

Border reduction

As mentioned above, semiconductor solar cells have an intrinsic dark current that is a function of the area of the cell. The junction or mesa area, A_{total} , is the total area in which the emitter and base layers are in contact (see figure 3). This includes all area under and beyond the primary or outer grid lines. The active device or window area, A_{active} , of the device can be defined as the area inside the primary grid lines. The current mid-energy and low-energy stack design include substantial junction area outside of the active device area. This is particularly a problem for concentrator cells, which have very small active area and therefore a larger ratio of total junction area to active area.

This inactive area behaves like a dark-diode in parallel with the active device, which reduces the open-circuit voltage and ultimately the power that the cell can produce. Both stacks in this system utilize 1 mm^2 active device areas. However, the junction area for the top cell in each

stack is 1.202 mm^2 and for the bottom cells 1.58 mm^2 (see Figure 1). The device open-circuit voltage is reduced by an amount

$$\Delta V_{oc} = \frac{nkT}{q} \ln \left(\frac{A_{total}}{A_{active}} \right) \quad (3)$$

The potential SPE gain for each cell was calculated by comparing the existing cell to a cell in which the dark-diode border were removed but operates at the same I_{sc} with the same ideality factor. The I_{sc} will increase minutely due to decreased recombination. The dark current can be reduced and V_{oc} could be improved by decreasing the junction area (see Figure 4). Calculations show that the total possible efficiency gain could be up to 0.40 absolute percentage points.

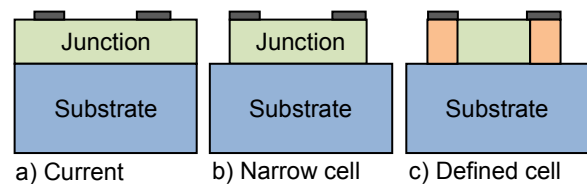


Figure 4. Possible border reduction designs. Diagram a shows the current design. Diagram b shows a cell with reduced junction area. Diagram c shows selective doping or passivation.

DEVICE STRUCTURE

Mid-energy GaInP window layer

The AlInP window of the GaInP cell aids in blocking minority carriers generated in the emitter of the cell from reaching the high recombination velocity top surface of the cell (see Figure 5).

Metal	
AlInP window	$E_G=2.4 \text{ eV}$
GaInP Emitter	$E_G=1.8 \text{ eV}$
GaInP Base	$E_G=1.8 \text{ eV}$
Tunnel junction	

Figure 5. Layers of the mid-energy GaInP cell

The AlInP layer is made of a wider band gap material than the GaInP base and emitter so that it absorbs as few photons as possible. Even so, the window absorbs a significant number of photons because it is only 0.6 eV wider than the GaInP layers. Some of the photons that are absorbed in the AlInP layer, close to the GaInP emitter, will be collected. However, photons that are generated near the front surface of the cell will be lost (see Figure 6).

The electrons generated to the right of the peak in the conduction band will move toward the emitter and be collected. The electrons generated to the left of the peak are swept by an electric field toward the top surface of the device where they are trapped and recombine.

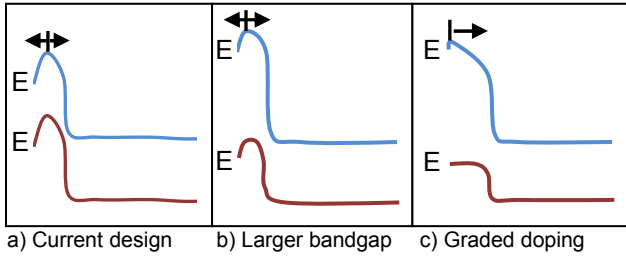


Figure 6. Options for reducing the GaInP cell window layer loss. Arrows point the average direction of current flow away from the peak the band of the AlInP window

This loss can be decreased by increasing the band gap of the window layer or by adjusting the location of the peak point in the conduction band toward the front surface of the window layer. Diagram 6a shows the current band structure of the window and emitter. Diagram 6b shows the same window layer with a wider band gap material. This increase would substantially decrease the number of photons absorbed in the window layer and thereby decrease the amount of current lost. Diagram 6c shows a window layer and emitter layer grading that effectively eliminates the loss of carriers in the window layer by forcing the peak in the conduction band nearer to the surface. In this case, most of the carriers generated in the window layer will be collected.

To determine the losses in the AlInP layer, the GaInP cell was first modeled using ADEPT with absorption in the window layer. Then absorption was removed in the window layer and the cell was modeled again. This shows what is possible if all of the absorption in the AlInP layer is eliminated. The elimination of losses due to the window contributes an additional 1 absolute percentage point to the SPE.

Absorption in the mid-Energy tunnel junction

Like the window layer of the GaInP cell, the tunnel junction is another area of the mid-energy cell where minority carriers can be generated and lost. While most of the photons above 1.8 eV are collected by the GaInP cell above the tunnel junction, if the band gap of the materials used in the tunnel junction are below 1.8 eV, they can absorb photons that would otherwise make it to the GaAs cell (see Table 2).

Originally, the two layers of the tunnel junction were made out of AlGaAs and GaAs. Both of these materials band gaps are below 1.8, and the GaAs at 1.42 eV was well below the 1.8 eV. This, coupled with the fact that these layers can be thicker than 100 nm, meant that a significant number of photons can be absorbed in these layers. While many of these photons were collected, some are not. In an effort to reduce the number of photons lost in the tunnel diode, the GaAs layer of the tunnel junction was replaced by a GaInP layer. This significantly reduced the

number of photons lost due in the tunnel junction. However the AlGaAs layer is still absorbing some photons.

Table 2. Mid-energy tunnel junction design

	Design	Previous	Current	Proposed
Window	AlInP window	Egap [eV]	Egap [eV]	Egap [eV]
GaInP cell	GaInP Emitter	1.8	1.8	1.8
	GaInP Base	1.8	1.8	1.8
Tunnel junction	AlGaAs	1.74	1.74	Higher
	GaAs/GaInP	1.42	1.8	1.8
GaAs cell	GaAs Emitter	1.42	1.42	1.42
	GaAs Base	1.42	1.42	1.42

Like the GaInP window layer, the tunnel junction AlGaAs/GaInP layers were modeled with and then without absorption using ADEPT. This allowed the effect of the absorption on the efficiency of the GaAs cell to be quantified. Through modeling of the absorption of these layers, it was determined that absorption in this layer only decreased the SPE of the GaAs cell by 0.12 absolute percentage points.

A number of things can be done to reduce the absorption in the AlGaAs layer. One possibility is to use a wider band gap material in place of the AlGaAs layer. Another option would be to invert the doping types of either the GaInP cell or GaAs cell and remove the tunnel junction all together. This has been show for in other tandem cell stacks [10].

DICHROIC AND ANTI-REFLECTION COATING

Dichroic optimization

The dichroic mirror is an important component in the optical system. It is difficult to design, due to the broad range of photon energies in the solar spectrum. It is also complicated by the angle of incidence of the incoming photons. In the present system, the high-energy photons are reflected by the dichroic mirror onto to the mid-energy cell, while the lower energy photons pass through the dichroic into the low-energy cells. The transition from reflective to transmissive is 20 nm wide for a single incidence angle.

Photons incident at different angles see a slightly shifted dichroic cutoff. As a result of the distribution of incidence angles, the effective transition from transmission to reflection of the dichroic mirror is more than 120 nm wide (see Figure 7).

With this understanding of the effective response cutoff width, we were able to calculate the improvement that could be realized if the effective width was decreased. It was determined that as much as 0.69 absolute percentage points in the SPE are being lost because of the broad dichroic response caused by the large angular distribution of the rays falling on the dichroic mirror.

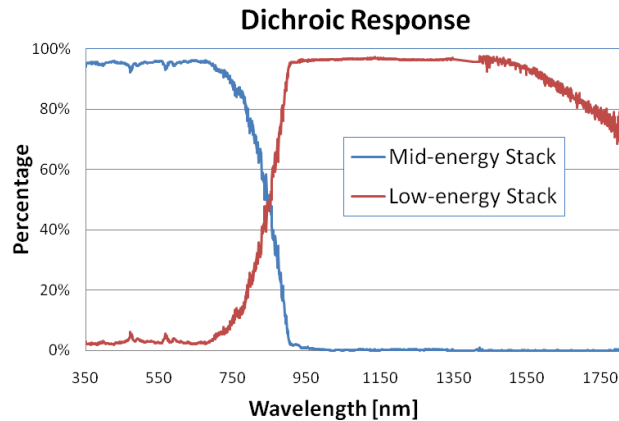


Figure 7. Modeled dichroic response as seen by the mid-energy and low-energy cells

Perfect anti-reflection coating

The last loss mechanism to be modeled was the anti-reflection coating. The anti-reflection coatings in this system are extremely good, and only reflect a very small percentage of the incident photons over the range of photon energies collected by the solar cells. While it is not possible to reduce the reflection to zero over the entire range of operation, it is informative to note the total amount lost due to reflection. To measure the improvement that a perfect anti-reflection coating would provide, the system was modeled in LightTools® with reflection [8]. The reflectance was then removed, and the efficiency with 0% reflectance or 100% transmission of the incident photons into the cells was determined.

CONCLUSION

Accurate and reliable solar cell models are critical to the success of the any concentrator solar cell research program. The magnitude of the losses for a four junction concentrator system composed of a GaInP/GaAs mid-energy stack and a GaInAsP/GaInAs low-energy stack have been modeled and evaluated. The three most important losses were resistance, absorption in the GaInP cell window layer, and surface reflection. Other losses such as absorption in mid-energy tunnel junction were found to be very small. This information can now be used by system designer to adjust the system design to minimize these remaining losses. The solar cell system described in this paper has been built and measured, with a SPE as high as 38.5%. Through the use of models we have shown that the SPE can be significantly improved by further optimizing the system design, perhaps to as much as 45% from these losses.

REFERENCE

- [1] Barnett, A., Honsberg, C., Kirkpatrick, D., *et al.*, "50% Efficient Solar Cell Architectures and Designs", *IEEE*

4th World Conference on Photovoltaic Energy Conversion, Vol. 2, pp.2560 – 2564, May 2006.

- [2] Allen Barnett, Douglas Kirkpatrick, Christiana Honsberg, *et al.* "Milestones toward 50% Efficient Solar Cell Modules", *22nd European Photovoltaic Solar Energy Conference*, September 2007.
- [3] A. L. Gray, *et al.*, "Multi-terminal dual junction InGaP/GaAs solar cells for hybrid system," *Proc. 33rd IEEE Photovoltaic Specialists Conference*, May 2008.
- [4] M.A. Steiner, *et al.*, "A monolithic three-terminal GaInAsP/GaInAs tandem solar cell," submitted to "Prog. Photovolt": Res. Appl., (2009).
- [5] Private communication with James D. McCambridge, Feb 3, 2009.
- [6] Martin Wolf, *et al.*, "Series Resistance Effects on Solar Cell Measurements", *Adv. Energy Conversion*, Vol. 3, pp.455-479, 1963.
- [7] J. Gray, "Adept: a general purpose numerical device simulator for modeling solar cells in one-, two-, and three-dimensions," *Proc. 22nd IEEE Photovoltaic Specialists Conference*, pp. 436–438 Vol. 1, Oct 1991.
- [8] J.R. Wilcox, *et al.*, "The combining of solar cell and optical modeling in multijunction systems", *Proc. 34th IEEE Photovoltaic Specialists Conference*, in press (2009).
- [9] A. W. Haas, *et al.*, "Numerical Modeling of loss mechanisms resulting from the distributed emitter effect in concentrator solar cells", *Proc. 34th IEEE Photovoltaic Specialists Conference*, in press (2009).
- [10] Myles A. Steiner, *et al.*, "A Direct Comparison of Inverted and Non-inverted Growths of GaInP Solar Cells", *Proc. 33th IEEE Photovoltaic Specialists Conference*, May 2008.

ACKNOWLEDGEMENT

This material is based on work funded by the DARPA Very High Efficiency Solar Cell program. The authors would like to thank Allen Gray at Emcore for mid-energy cell data, Myles Steiner at National Renewable Energy Laboratory for low-energy cell data, Keith Emery at National Renewable Energy Laboratory for cell measurements, Blair Unger at the University of Rochester, Roger Buelow, Timothy McCollum and Laszlo Takacs of Energy Focus, Inc. for their help with the optical model. This document was cleared by DARPA on 6/5/2009: Approved for Public Release, Distribution Unlimited.